AD/A-003 837

HEAT AND MOISTURE TRANSFER IN CLOTHING SYSTEMS. PART I. TRANSFER THROUGH MATERIALS, A LITERATURE REVIEW

Rita M. Crow

Defence Research Establishment
Ottawa, Ontario

25 September 1974

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

AD/A-003437

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1 ORIGINATING ACTIVITY Defence Research Establishment Ottawa, National Defence Headquarters, Ottawa, Canada. K1A 0Z4	2a DOCUMENT SECURITY CLASSIFICATION Unclassified 2b GROUP n/a

3 DOCUMENT TITLE

HEAT AND MOISTURE TRANSFER IN CLOTHING SYSTEMS. PART 1. TRANSFER THROUGH MATERIALS, A LITERATURE REVIEW

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Note

5 AUTHOR(S) (Last name first name middle initial)

CROW, Rita M.

6 DOCUMENT DATE 25 September, 1974	7a TOTAL NO OF PAGES 18	7b NO OF REFS 62

8a PROJECT OR GRANT NO 79-01-04	9a ORIGINATOR'S DOCUMENT NUMBER(S) DREO Technical Note No. 74-27
8b CONTRACT NO	9b OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document)

10 DISTRIBUTION STATEMENT

UNLIMITED

11 SUPPLEMENTARY NOTES	12 SPONSORING ACTIVITY

13 ABSTRACT

UNCLASSIFIED

The complexities of the effect of variables, in particular moisture, on thermal insulation of cold weather clothing are introduced. A literature review of the methods for measuring heat transfer, moisture diffusion and combined heat and moisture transfer is presented. The effects of variables on heat transfer and moisture diffusion are reviewed in detail. The theoretical equation for combined heat and moisture transfer is derived, and compared to experimental results of various workers.

DSIS
72-04

UNCLASSIFIED

Security Classification

KEY WORDS

Heat

Moisture

Fabrics

Thermal diffusivity

INSTRUCTIONS

1 ORIGINATING ACTIVITY Enter the name and address of the organization issuing the document

2a DOCUMENT SECURITY CLASSIFICATION Enter the overall security classification of the document including special warning terms whenever applicable

2b GROUP Enter security reclassification group number The three groups are defined in Appendix 'M' of the DRB Security Regulations

3 DOCUMENT TITLE Enter the complete document title in all capital letters Titles in all cases should be unclassified If a sufficiently descriptive title cannot be selected without classification show title classification with the usual one capital letter abbreviation in parentheses immediately following the title

4 DESCRIPTIVE NOTES Enter the category of document, e g technical report technical note or technical letter If appropriate enter the type of document e g interim progress, summary annual or final Give the inclusive dates when a specific reporting period is covered

5 AUTHOR(S) Enter the name(s) of author(s) as shown on or in the document Enter last name, first name middle initial If military show rank The name of the principal author is an absolute minimum requirement

6 DOCUMENT DATE Enter the date (month year) of Establishment approval for publication of the document

7a TOTAL NUMBER OF PAGES The total page count should follow normal pagination procedures i e , enter the number of pages containing information

7b NUMBER OF REFERENCES Enter the total number of references cited in the document

8a PROJECT OR GRANT NUMBER If appropriate enter the applicable research and development project or grant number under which the document was written

8b CONTRACT NUMBER If appropriate, enter the applicable number under which the document was written

9a ORIGINATOR'S DOCUMENT NUMBER(S) Enter the official document number by which the document will be identified and controlled by the originating activity This number must be unique to this document

9b OTHER DOCUMENT NUMBER(S) If the document has been assigned any other document numbers (either by the originator or by the sponsor), also enter this number(s)

10 DISTRIBUTION STATEMENT Enter any limitations on further dissemination of the document other than those imposed by security classification, using standard statements such as

(1) "Qualified requesters may obtain copies of this document from their defence documentation center."

(2) "Announcement and dissemination of this document is not authorized without prior approval from originating activity "

11 SUPPLEMENTARY NOTES Use for additional explanatory notes

12 SPONSORING ACTIVITY Enter the name of the departmental project office or laboratory sponsoring the research and development Include address

13 ABSTRACT Enter an abstract giving a brief and factual summary of the document, even though it may also appear elsewhere in the body of the document itself It is highly desirable that the abstract of classified documents be unclassified Each paragraph of the abstract shall end with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (TS), (S), (C), (R), or (U)

The length of the abstract should be limited to 20 single spaced standard typewritten lines 7½ inches long

14 KEY WORDS Key words are technically meaningful terms or short phrases that characterize a document and could be helpful in cataloging the document Key words should be selected so that no security classification is required Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context

RESEARCH AND DEVELOPMENT BRANCH

DEPARTMENT OF NATIONAL DEFENCE
CANADA

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE NO. 74-27

HEAT AND MOISTURE TRANSFER IN CLOTHING SYSTEMS. PART 1. TRANSFER THROUGH MATERIALS, A LITERATURE REVIEW

by

R.M. Crow
Environmental Protection Section
NBC Defence Division

PROJECT NO.
79-01-04

i b

RECEIVED OCTOBER 1974
PUBLISHED OCTOBER 1974
OTTAWA

74-311

IMPORTANT NOTICE

CAUTION

This information is furnished with the express understanding that proprietary and patent rights will be protected.

The above Securitv Caution was inadvertently omitted from the inside front cover during the printing of

DREO Technical Note No. 74-27

The DSIS Publishing Section regrets any inconvenience this may have caused.

ABSTRACT

The complexities of the effect of variables, in particular moisture, on thermal insulation of cold weather clothing are introduced. A literature review of the methods for measuring heat transfer, moisture diffusion and combined heat and moisture transfer is presented. The effects of variables on heat transfer and moisture diffusion are reviewed in detail. The theoretical equation for combined heat and moisture transfer is derived, and compared to experimental results of various workers.

RÉSUMÉ

Il s'agit dans ce rapport des problèmes complexes créés par les effets de variables, tout particulièrement de l'humidité, sur l'isolation thermique des vêtements d'hiver. On présente une revue de la littérature traitant les effets de ces variables sur l'isolation thermique, sur la diffusion de l'humidité et sur les méchanismes de transmission de la chaleur et de l'humidité de même que les méthodes pour mesurer ces propriétés et les formules pour les décrire théoriquement.

TABLE OF CONTENTS

Preceding page blank

1. INTRODUCTION

In order to maintain effective land forces in an Arctic winter, it is essential that they should be relieved, as far as is practicable, of the burden of struggling with environmental hazards. It has been said that the soldier under Arctic winter conditions spends most of his time merely trying to survive, and this, of course, reduces his efficiency as a fighting man.

The main enemies are bitter cold and high winds, and to protect against these the soldier must have specially designed clothing. This clothing must have very good thermal insulating properties, and also windproofness to a great degree. However, warm and windproof clothing brings further difficulties, due to the fact that, as presently designed, it is not easily adjustable to take account of changes in activity of the soldier. The result can often be that he gets overheated, and sweats, thus causing excessive amounts of moisture to accumulate inside the clothing. Under cold external conditions some of this moisture will condense to water or even to ice in the outer layers of clothing. The change from water vapour to liquid water is one in which a large latent heat is given up, and the further change to ice also releases significant amounts of thermal energy.

Hence a very complex situation arises in thick, Arctic clothing. Heat transfer from the man's body to the environment is not just a simple conduction through a thick layer of material of constant insulation value. Moisture plays a very prominent role in the transfer of the energy, and a role that changes with activity. In addition to transfer of latent heat by diffusion through the spaces of various materials, water vapour may be absorbed by the fibres giving rise to a further exothermic change, and the thermal conductivity of the wet fibres then becomes very different from that of the dry fibres. When the soldier ceases the activity which caused sweating, he will lose heat more rapidly through the wet insulation, than he would through the same insulation when dry, and this may cause chilling.

These problems with moisture are very difficult to deal with in designing efficient military cold weather clothing. Although many improvements have been made in military clothing over the past two decades, land forces in an Arctic winter environment still suffer from frostbite and cold discomfort, showing that the problems of protection have not been solved, and therefore emphasizing their complexity.

The ideal solution would be an air-conditioned clothing system in which the air immediately surrounding the body is maintained at a comfortable temperature and humidity. This type of system has been successfully invented by NASA, and used by the astronauts on the moon. However, in its present form, many of its features make it impractical for standard cold weather clothing issue, and the cost is formidable. Therefore, an alternative solution must

be found. To achieve this, a close examination of the two basic principles of air conditioning is required - namely the heat and moisture transfer mechanisms. A thorough understanding of these mechanisms is essential before advances can be made in materials and clothing design. This paper will deal with materials of good thermal insulating properties as used for Arctic clothing and will review

1. the methods of measuring
2. the equations for
3. the effect of variables on

the heat and moisture transfer mechanisms separately, and then in combination. The influence of the heat of absorption by the fibres will be omitted.

2. HEAT TRANSFER

The modes of heat transfer between two surfaces can be conduction, convection and radiation. Since the methods for measuring the effect of variables on heat transfer consider either heat flow from a heat source to the outer surface of the material (mainly by conduction) or heat flow from the heat source to the atmosphere (by conduction, radiation and convection), the all-encompassing and reciprocal term of 'thermal insulation' will be used. The thermal insulating power is defined as the property of a material which resists heat flow and thus reduces heat loss from the heat source, e.g. the human body.

2.1 METHODS OF MEASUREMENT

Morris (1), in an excellent review of the literature on the thermal properties of textile materials, covering the years 1930 to 1950, classified the methods, then available, for measuring the thermal insulation of fabrics as the cooling method, the constant temperature method and the disc method. Both the cooling method and the constant temperature method take into account heat loss from the outer surface by radiation and convection as well as conduction through the clothing system. For the cooling method (2,3,4,5), a hot body whose outer surface is exposed to the air is covered with fabric and the rate at which the body cools is determined. For the constant temperature method the fabric is wrapped around a hot body and the energy required to maintain the body at this constant temperature is measured. Baxter and Cassie (6) defined the percent reduction of heat loss when the hot body is covered with fabric as the Thermal Insulating Value, T.I.V. In an alternative method (7), the equilibrium temperature at a constant power input is measured with and without the heat source covered with a test fabric. Again, the percentage decrease in heat loss with the fabric in place is a measure of the fabric's insulating power. The constant temperature method has been used extensively (8-14) by workers since Morris's review, because, as Morris points out, the conditions are similar to those which occur in actual wear.

The disc method (15,16,17,18) measures the heat flow across a test fabric to imitate the heat flow from the body to the outer surfaces of the clothing. In this method, the fabric is held in place between two plates which are maintained at different temperatures. The rate of heat flow (which has been measured in terms of power, current or the actual heat flow) across the temperature gradient is measured and the thermal conductivity constant, k, is determined where

$$k = \frac{d\theta}{dt} \frac{d}{(T_1 - T_2)\ A}$$

and $d\theta/dt$ is the rate of heat transfer
d is the thickness
A is the area perpendicular to the direction of heat flow
$(T_1 - T_2)$ is the temperature gradient across the thickness.

Whenever this constant, k, is used to describe the thermal conductivity of textile materials, it is re-defined as the rate of heat transfer per unit temperature gradient to include all possible modes of heat transfer down the temperature gradient, not just heat transfer by conduction. To emphasize this point, the term 'thermal conductivity' often is replaced by 'thermal transmissivity', 'heat transmission' or instead, the reciprocal, 'resistivity' is used. The latter is expressed in units of Clo, Tog or T-ohm. A Clo is the amount of insulation that will allow the passage of 1 calorie per square meter per hour with a temperature gradient of 0.18°C between two surfaces. It is defined by the equation (19)

$$H = \frac{T_s - T_a}{I}$$

where H is the rate of dry heat loss per unit area
T_s is the skin temperature
T_a is the ambient temperature
I is the thermal resistance of the clothing plus the overlying air layer.
1 Clo is equal to 1.55 Togs and 15.5 T-ohms.

A recent method for measuring thermal insulation (20) is somewhat similar to the disc method, but simpler. It is based on the principle that the ratio of the temperature drop across conductors in series, with respect to the direction of heat flow, equals the ratio of their thermal resistances. The thermal resistance of an unknown material is found by measuring the temperature drop across it and across a material of known resistance.

2.2 EFFECT OF VARIABLES

Despite the use of more sophisticated equipment for measuring thermal insulation in recent years, very little new evidence has been published about the effect of variables on thermal insulation since Morris's review (1) of the work done on the subject prior to 1950.

The thermal insulating value of a textile material is almost totally dependent on the amount of air in the material. The reason is simply because the thermal insulating value of air is significantly greater than that of fibres. One source (21) gives the thermal insulation of a fibre pad (density of 0.5 g/cm^3) to be about one sixth that of air. Therefore it is logical that the thermal insulating power afforded by a textile material is primarily determined by its thickness and density.

Workers have verified that thermal insulation varies directly as the thickness of the material, whether the variation in thickness was obtained by adding successive layers of the same material (5,11,18,22,23,24, 26,27), by altering the thickness of the material by changing the pressure per unit area (16,18,25) or by testing a range of fabrics with varying thickness (6,7,12,27). For all practical purposes, the first method holds the density of the material constant while the effect of increasing thickness on thermal insulation is measured, with the result that the thermal insulation is additive for each successive layer (24,26,27), if the surface of the material is smooth (23). The second method increases the density as the thickness of the material is decreased. This results, of course, in a negative correlation between thermal insulation and density (24,26,28,29), to a limit where any further change in density has little or no effect on changing the thermal insulation (27). However, when Speakman and Chamberlain (18) held the thickness of a mass of loose fibres constant and varied the density from 0.01 to 0.16 g/cm^3, they found that the change in thermal insulation of the mass was insignificant. This apparent discrepancy may be explained in a paper by Peirce and Rees (27). They stated that the thermal insulating value of a low density batting approaches that of still air. Any change in density of this batting causes a decrease in thermal insulation. When the density of the batting is reduced, convection within and radiation through the batting decreases its insulating power. When the density of the batting is increased, the increase in heat transfer is mainly by conduction through the fibres. Since the fibres have a higher conductivity than air, the thermal insulation again will be decreased. It would appear that the variation in density is not great enough in Speakman and Chamberlain's work to dramatically change the mode of heat transfer and thus give a significant change in thermal insulation.

Changes in thermal insulation due to wear, or after laundering or dry cleaning are closely associated with changes in thickness. Wear tends to decrease fabric thickness and therefore tends to decrease thermal insulation. Cleaning the fabric will increase its thickness and thus its thermal insulation if the fabric shrinks or if it is fluffed up during drying or pressing (4,30,31,32). Starching has no effect on thermal insulation (32).

Two factors determine the effect that 'fabric' construction has on thermal insulation. The first factor, of course, is the amount of air contained within the structure. Thus napped and pile fabrics (12,18), quilted waddings and felts (6), and polyurethane foams (5,26) have greater thermal insulating power than smooth fabrics. However, the insulation value differed very little when the count of a plain weave fabric was varied from 23 to 50 threads per inch in the warp or from 21 to 43 threads per inch in the weft (4). The second factor is the direction of fibre arrangement, that is, whether the fibres lie parallel or perpendicular to the fabric surface. Finck (33) showed that thermal insulation was two to three times greater when the fibres were arranged parallel rather than perpendicular to the fabric surface. Bogaty et al's work (16) confirmed these results. In addition, Speakman and Chamberlain (18) found that a parallel fibre arrangement gave a higher insulating value than a disoriented fibre mass. These results support the findings of Gillings et al (22) that the warmth to weight factor of polyester battings is higher than that of pile fabrics.

No relationship has been found between the weight of fabrics and their thermal conductivity (6,12). However, Rees (24) pointed out that heavier fabrics would tend to be thicker and so have a higher thermal insulating power than thinner, lighter fabrics.

Aelion and Brown (12) found cotton to be a better insulator than wool. In contrast, several workers (6,11,18,29,34) all found wool to be the best insulator and cotton the worst. In the cases tested by these workers, the synthetic fibres fell in between these two fibres.

It has been shown that it is the space at which the garment is worn from the body rather than the kind of fibre or material from which it is made, which has the greater effect on its value as an insulator. Black and Matthews (4) determined that maximum insulation occurs when there is 0.3 to 0.375 inches of air between the body and the fabric; Rees (24) gives this value to be 0.35 inches and Latham (7) as 0.19 inches. In testing several sets of underwear-outerwear combinations, Fonseca (9) found the underwear layer simply replaced this still air layer between the outer fabric and the body without adding insulation to the ensemble. He concluded that the outer fabric was the deciding factor in determining the thermal characteristics of complete clothing systems. Other workers (4,13,24,35) have discovered this was particularly true if the thermal insulation of the fabrics was measured in a wind, when the thermal insulation drops sharply to a limiting value as the wind velocity increases. This drop is less severe for closely woven fabrics than for open, porous fabrics (14,24). Niven (35) found that the drop in thermal insulation was less if the wind was blowing parallel, rather than at right angles, to the sample.

Other external atmospheric conditions affect thermal insulation also. For instance, thermal insulation decreases as the temperature increases (5,24,36,37). Hammel (36) calculated an increase of 0.5 Clo/in. for fur when the temperature was lowered from 20°C to -50°C. Further, thermal insulation varies inversely with the relative humidity of the air (11,34) with a relationship approximating a second order equation (25,38). Black and Matthews (4) showed that the effect of increasing moisture is most

pronounced over the range of 0 to 75% R.H. However, Rees (24) stated that any change in ambient humidity which would be met in wear would have little effect on the thermal insulation of the material, provided there was no evaporation from the fabric surface. Rees' statement would agree with Black and Matthews' finding if Rees was referring to ambient conditions in Great Britain where the relative humidity would be above 75% for the majority of the year.

Figures have been given for the decrease in thermal insulation with the increase in relative humidity - 10% for wool and 3% for cotton with a 55% increase in relative humidity (2?), and a 1% decrease for each 5% increase in water vapour (29).

Further, a linear relationship has been found to exist between thermal insulation and the moisture content of a fabric (29,38,39). Hollies (34) found that thermal insulation is independent of the standard regain of fibres, as measured at 22°C and 65% R.H. However, all fabrics regardless of fibre content, have approximately the same thermal insulating value when wet (4,24), this being about three times less than the insulating value of a dry fabric.

Finally, when the air, in and around the fur of a pelt, is replaced by the gas Freon, the insulation per unit thickness of the fur is increased about four times (36).

In summary, the following factors increase thermal insulation:

1. Increase in thickness
2. Decrease in density (or an increase in porosity)
3. Increase in the number of fibres lying parallel to the fabric surface
4. Decrease in the number of times a fabric is worn
5. Dry cleaning or laundering
6. Decrease in wind velocity
7. Decrease in temperature
8. Decrease in moisture content of the fibres.

3. DIFFUSION OF MOISTURE

When there is a water vapour gradient across a porous material, such as a fabric, the water vapour from the side of higher concentration diffuses through the fabric to the side of lower water vapour concentration. The basic equation to describe this process was first presented by Fick (21), and gives 'the rate of transport $\frac{dm}{dt}$ of the diffusing substance across an area A of a plane perpendicular to the concentration gradient $\frac{\delta c}{\delta x}$ as

$$\frac{dm}{dt} = -DA\,\frac{\delta c}{\delta x}$$

where D is the diffusion coefficient' (12). Authors of books (40,41) and papers (42) use this basic equation as a launching point for involved and sophisticated mathematical treatment of the diffusion process. However, most workers in the clothing and textile field prefer a simple and practical form of this equation to evaluate the water vapour transmission or, its reciprocal, the resistance to water vapour diffusion.

3.1 METHODS OF MEASUREMENT

The ASTM methods (43,44) measure the flow of water vapour through unit area of material in unit time, with the results expressed by the derived equation

$$WVT = Q/tA$$

where WVT is the water vapour transmission
Q is the grams of water vapour passing through the fabric
t is time.

For the basic method the test material is fastened over the mouth of a dish containing either a desiccant or water. This apparatus is placed in an atmosphere of constant temperature and humidity, and its loss or gain in weight, with time, is used to calculate the rate of water vapour movement through the material. The conditions of relative humidity in the dish (water or desiccant), the relative humidity outside the dish, and the ambient temperature are selected according to the end use and the permeability characteristics of the test material.

These methods were originally designed for materials which had low water vapour permeability, or high resistance to water vapour transmission. Therefore, they are not appropriate for evaluating the transmission properties of porous textile materials, which have low resistance to water vapour diffusion. The reason is simply that layers of still air are formed on both sides of the test material, and offer resistance to water vapour flow of a magnitude approximating that of the textile material under test (45,46).

Two test methods have been developed to eliminate the error introduced by the resistances of these air layers. One method directly measures the resistance to water vapour diffusion (47), as derived from Fick's law (45)

$$R = 1/Q\ D\ \Delta c\ A\ t$$

where Δc is the difference in vapour concentration on either side of the fabric. This resistance, R, as applied to fabrics, would be the equivalent resistance of a given height of still air, usually expressed in centimeters. D is calculated from the diffusion equation, simplified by the authors for practical use between 0 and 50°C:-

$$D = 0.220 + 0.00147\ T \text{ (where T is in °C)}$$

Likewise, Δc, at a constant temperature is

$$\Delta c = 2.89 \times 10^{-4} \times \Delta p / T^{\text{absolute}}$$

where Δp is saturation vapour pressure difference in mm Hg. In this method, A is held constant, and Q/t found experimentally for 1, 2 and 3 layers of fabric. The layers are placed on top of each other so that no additional air space is added. R is then calculated for the layer(s) and 'the intrinsic resistance of a fabric is defined as the difference in total resistance caused by an additional layer of fabric' (47).

It would be appropriate to interject here Weiner's equations for approximating cotton fabric resistance and water vapour transmission.

$$\text{Resistance (cm)} = \text{Thickness (cm)} + 0.02 \text{ Weight (oz/yd}^2)$$

$$\text{Water Vapour Transmission (g/m}^2 \text{ 24 hr)} = 1/212.98 \, R\Delta p$$

where Δp is the vapour pressure difference across the fabric in mm Hg.

In the Control Dish Method (46,48,49) the rates of diffusion are measured through three sets of control fabrics, placed at three levels or 'air thicknesses' above layers of water in control dishes. From these results, the equation of the line relating the rate of diffusion to each 'air thickness' is calculated. A test specimen is placed in another dish, between the control fabric and the water, and the subsequent rate of diffusion found. This value is inserted into the 'control' equation and the overall equivalent air thickness due to the addition of the test fabric to the system is calculated. This value is then subtracted from the actual measured air thickness in the system to give the test fabric's equivalent resistance to water vapour diffusion in centimeters of still air.

Woodcock (50) took a completely different approach to the measurement of water vapour diffusion. He argued that the measurement of the resistance to diffusion through a textile material is a static one, and that a more meaningful measurement would be one which included the removal of the diffusion vapour from the outer surface of the material by a moving air mass. He therefore introduced the moisture permeability index, denoted by i_m, to describe this latter mechanism. A full explanation of Woodcock's permeability index is given elsewhere (22). It suffices to state here that this index is based on the wet and dry bulb thermometer principle, where

$$i_m = \frac{T_a - T_s}{S(p_s - p_a)}$$

and T_a is ambient temperature, T_s skin temperature, S a constant, p_s the saturation vapour pressure at T_s, and accordingly, p_a the partial vapour pressure at T_a.

Woodcock's apparatus to measure this index is a guarded copper cylinder, covered with a linen wick. Cellophane covers the wick to prevent wetting of the test fabric. The whole assembly is placed in a wind tunnel and when adiabatic equilibrium is attained, T_a, T_s, p_a and p_s are measured, and i_m calculated.

3.2 EFFECT OF VARIABLES

The effects of atmospheric variables on the rate of water vapour transmission are as follows. This rate increases as

1. vapour pressure gradient across the fabric increases
2. ambient temperature increases
3. atmospheric pressure increases.

However, the effects of fiber or fabric properties on this diffusion process are not as well defined as those of atmospheric variables. The main reason seems to be that the two 'classical' studies on the subject, one by Fourt and Harris (47) and one by Whelan et al (49) interpret their results from two conflicting points of view. Fourt and Harris established that the major part of the diffusion process is through the fibres, and thus explain all their other results in terms of the hygroscopic properties of the fibers. Whelan et al found that the amount of diffusion through fibres is within experimental error, and thus, for most fabrics, negligible. They base their discussion of results on what they consider to be the most important variable affecting water vapour transmission - the quantity of fibre in the material, i.e. thickness and percentage fibre volume. Subsequent results, for the most part, have related to one or the other theory. Nordon and Downes (51) and Subramanian (52) support Whelan et al, Knight et al (53) follow Fourt and Harris's theory. Earlier work by Peirce et al (54) agreed with Fourt and Harris's work.

There is a general positive correlation between fabric thickness and water vapour resistance (49,52,54). When Whelan et al (49) held the percent fibre volume (20-29%) constant, a definite linear relationship emerged between thickness and resistance. They concluded that the initial scatter obtained was due to the extreme values of percent fibre volume. On the other hand, Fourt (47) found that fabrics with less than 30 to 40% fibre volume had similar resistances. Further, above this percentage, the resistance increased more rapidly with percent fibre volume, the more hydrophobic the fibre. Others did not find this to be so (49,52).

Subramanian (52) measured the water vapour transmission of fabrics made from hydrophobic fibres (over 40% fibre volume) before and after they were laminated to a foam sheeting, and after the laminate was waterproofed with a 'polyurethane-adhesive formulation'. He found no correlation between water vapour transmission and fibre volume.

Fourt's results (47) showed that there was little relationship between air permeability and vapour permeability for hygroscopic fibres, and Peirce et al (54) found no relation whatsoever. Knight et al (53) found that incremental increases of synthetic fibre in synthetic-cotton knitted fabrics gave corresponding increases in both water and air permeability. However, it was concluded that the increase in the water vapour permeability may be due to the moisture regain of the fibres, rather than the air permeability characteristics of the fabrics.

Water repellent finishes had no effect on the water vapour permeability of the fabrics (47,54). Gillings et al (22) found continuously coated fabrics (with hydrophobic coatings) to be impermeable to water vapour, and those fabrics with 'microporous' coatings had permeabilities much lower than uncoated fabrics. Subramanian (52) found that water-proofing his laminate decreased its vapour permeability by 40%, but not to 0, although the air permeability was reduced to zero. When Peirce et al (54) coated a fabric with a hygroscopic layer, the water vapour transmission remained constant, although the air permeability was decreased, and water repellency increased. Work on films revealed that water vapour transmission through films increased with the hygroscopic characteristics of the film (49). The addition of plasticisers to films also increases their water vapour transmission (55).

Some workers (54,55) found water vapour resistances are additive for increasing layers of fabric. Whelan et al did not (49). They pointed out that the resistance per layer in a multi-layer system depends on the amount of contact between layers and the surface characteristics (i.e. smoothness and hairiness) of the fabric. It will be recalled that Fourt and Harris (47) base their whole experimental method on the linear relationship between fabric layers and resistance!

Finally, Gillings et al (22) found very little correlation between the moisture permeability index and fibre type and fabric construction.

4. HEAT AND MOISTURE TRANSFER

There have been two distinct approaches in investigations of this combined effect of heat and moisture transfer through materials. The first considers heat and moisture transfer through any material in terms of thermal or equivalent thermal conductivity. The second is an extension of Woodcock's permeability index theory to include heat loss due to a temperature gradient as well as the vapour gradient across the clothing system. This is accomplished by adding the Clo and i_m values, or using a ratio of the two in an attempt to attain a more meaningful parameter. Since both Clo and i_m values have already been explained earlier, and since the experimental work combining the two has been more or less limited to 'in house' comparisons of clothing systems, the discussion of this topic will be terminated here.

The methods used to measure heat and moisture transfer are, for the most part, the same as those described earlier for measuring thermal insulation, e.g. the constant temperature method (11,34), the cooling method (28), and the temperature drop across materials of known and unknown resistances method (59). The exception is the dynamic Angstrom method, in which the propagation velocity of a heat wave through a porous material is measured (56,60). The thermal diffusivity and subsequently the thermal conductivity of the material are obtained.

4.1 THEORETICAL CONSIDERATION

Heat loss from the body through layers of damp or wet clothing involves a three phase system, composed of the solid (fibre and/or ice), the liquid (water) and the gas (air and water vapour). The boundaries of the system are defined by the surfaces of the inner and outer layers. In such a system (56), there are seven heat transfer mechanisms which operate simultaneously:

1. conduction in the solid phase
2. conduction in the liquid phase
3. conduction in the gas phase
4. radiation through the gas phase
5. convection through the liquid phase
6. convection through the gas phase
7. evaporation-diffusion-condensation-solidification.

Heat transfer by radiation and convection between two surfaces is usually ignored by workers in the field (33, 56-59) because neither contributes significantly to the total heat transfer as compared to that by conduction. Nissan (56) calculated that for the woven staple fibreglass sheets used in his study, radiation would account for less than five percent of the total observed heat transfer, and natural convection would account for less than radiation. Large pores and high temperatures (58,59) would be required to make either type of heat transfer significant. The major heat transfer methods are therefore conduction in the solid, liquid and gaseous phases with thermal conductivities of k_s, k_w and k_g respectively, and the evaporation-diffusion-condensation mechanism.

In order to obtain a total equation for heat transfer across defined boundaries of a system, and thus to calculate theoretical values for the effect of moisture on this heat transfer, an equivalent conductivity for the evaporation-diffusion-condensation mechanism is used. Nissan et al (56) have derived this equivalent conductivity k_D, which is essentially the product of the latent heat of evaporation, λ, and the rate of diffusion across the system:

$$k_D = \lambda \frac{DM}{RT} \frac{P_T}{P_T - P} \frac{dP}{dT}$$

where D = diffusion coefficient
M = molecular wt.
R = gas constant
T = absolute temp.
P_T = total pressure
P = saturated vapour pressure.

Workers (34,39,56, 59-61) have agreed on the general form of the equations for conductivity through a porous system, using either a three phase, or the simpler two phase system. The parameters associated with each phase are its thermal conductivity, its phase distribution and its volume fraction (59).

When heat flow by conduction is across more than one phase, as it is here, the direction of heat flow with respect to the phases becomes important in determining the total conductivity of the system. This, of course, is analogous to the transmission of electricity, as expressed by Ohm's Law.

If heat flow is across each individual phase in turn, or in series, (Figure 1A), the thermal conductivity is at a minimum:

$$\frac{V_s}{k_s} = \frac{V_f}{k_f} + \frac{V_w}{k_w} + \frac{V_g}{k_g} + \frac{V_D}{k_D}$$

where the total volume in series

$$V_s = V_f + V_w + V_g + V_D = 1$$

and V_f, V_w, V_g, V_D are volume fractions of fibre, liquid, gas and equivalent volume of diffusion respectively.

If the heat flow is parallel to the phases (Figure 1B), the thermal conductivity will be at a maximum:

$$V_p k_p = V_f k_f + V_w k_w + V_g k_g + V_D k_D$$

where the total volume in parallel

$$V_p = V_s = 1$$

In textile materials, it is the solid or fibre phase which determines the direction of the three phases relative to the direction of heat flow. This has been confirmed by work that has shown thermal conductivity is at a maximum when the direction of heat flow is parallel to the fibres, and at a minimum when it is normal to the fibres (33,39). Since very few systems have their solid phases lying either parallel or normal to the direction of heat flow, weighted proportions of each are added together to give the empirical expression for thermal conductivity across a very narrow width of the system (Figure 1C)

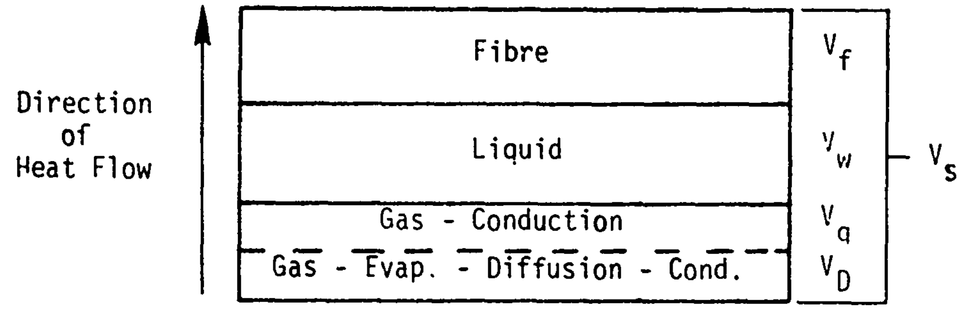

Fig. 1A. Heat flow in series.

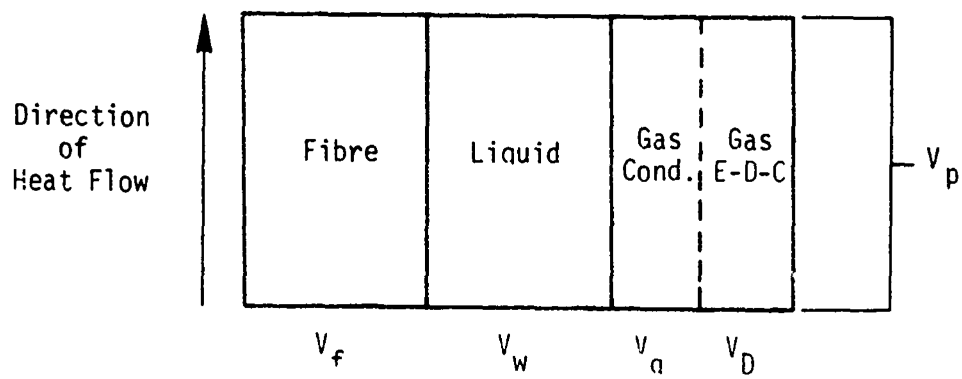

Fig. 1B. Heat flow in parallel.

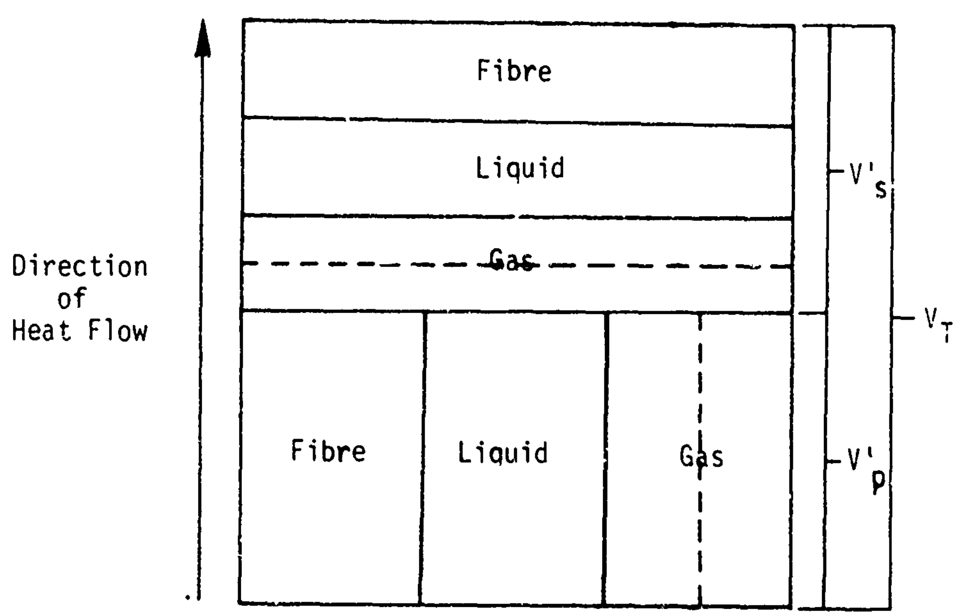

Fig. 1C. Heat flow in a total system.

$$V_T k_T = V'_s k_s + V'_p k_p$$

where the overall total volume $V_T = V'_s + V'_p = 1$.

There is good agreement between this theoretical equation, or a form of it, and experimental results. It was found that heat transfer rates are increased by the diffusion mechanism, especially at temperatures above room temperature (56, 60-62). However, a better understanding of the mechanisms is yet to be attained (56,61,62). Maximum heat transfer is found to occur at intermediate values of liquid saturation (56,60).

Workers have investigated the effect of the predominant moisture phase and the location of the water molecules of the liquid phase on thermal conductivity. Joy (61) found that thermal conductivity rises abruptly once the temperature falls to 0°C, and the liquid water in the system solidifies. Hollies and Bogaty's work (39) revealed that the condensation of water vapour on the surface of a material markedly increases the conductivity of the material. The major cause (29,33) for this is that liquid water reduces the contact resistance between fibres and thus increases the thermal conductivity of the system. A contributory factor (29) is that water molecules, in attaching onto local sites on the fibre, swell them to increase the density of the system and thus increase the thermal conductivity. Hollies and Bogaty (39) found that on an absolute basis, losses in thermal resistance due to moisture are greater than losses due to changes in fibre arrangement. However, insulating materials have a maximum total conductivity when the material arrangement is parallel to the heat flow, and a minimum total conductivity when this arrangement is in series with respect to heat flow. In both cases, the total conductivity increases with the moisture content of the materials (61).

5. REFERENCES

1. Thermal Properties of Textile Materials, G.J. Morris, 1953, J. Text. Inst. 44, T449.

2. A Simplified Hot Plate Apparatus, C.D. Niven, 1962, Text. Res. J. 32, 890.

3. Some Effects of Absorbency of Clothing Materials, R.L. Pratt, G.F. Fonseca and A.H. Woodcock, 1956, Quartermaster Research and Development Center, US Army, Natick, Massachusetts. Environmental Protection Research Division, Research Study Report, BP-3.

4. The Physical Properties of Fabrics in Relation to Clothing, C.P. Black and J.A. Matthew, 1934, J. Text. Inst., 25, T249.

5. Dry Thermal Insulation of Thick Clothing, L. Fourt, G.A. Lyerly, G.C. Edwards and E.D.W. Poland, 1960, Quartermaster Research and Engineering Center, U.S. Army, Natick, Massachusetts. Textile Engineering Laboratory Report No. 263.

6. Thermal Insulating Properties of Clothing, S. Baxter and A.B.D. Cassie, 1943, J. Text. Inst. 34, T41.

7. The Structure of Shirting Fabrics in Relation to Comfort in Wear. B.J. Latham, 1973, Cloth. Res. J. 1, 3.

8. American Standards on Textile Materials (D 1518-64) 1973, American Society for Testing Material.

9. Heat Transfer Properties of Ten Underwear-Outerwear Ensembles, G.F. Fonseca, 1970, Text. Res. J., 40, 553.

10. A Simple Method of Measuring the Thermal Transmission of Fabrics, H.G. David, 1963, Text. Res. J., 33, 322.

11. Comfort Properties of Blankets, R.J. Rowlands, 1963, Text. Res. J. 33, 343.

12. The Effect of Certain Physical Characteristics of Fabrics Upon Heat Transmission, D.L. Aelion and H.C. Brown, 1956, Bulletin Lowell Technological Institute 3, 3.

13. The Thermal Insulation of Caribou Pelts, I. Moote, 1955, Text. Res. J., 25, 832.

14. The Prediction of Equilibrium Thermal Comfort from Physical Data on Fabrics, H.B. Hardy, J.W. Ballou and O.C. Wetmore, 1953, Text. Res. J., 23, 1.

15. American Standards on Textile Materials (C-177-45) 1958, American Society for Testing Material.

16. Some Thermal Properties of Fabrics, H. Bogaty, N.R.S. Hollies and M. Harris, 1957, Text. Res. J., 27, 445.

17. Simplified Method for the Measurement of Heat Transmission of Fabrics, E.R. Schwartz, 1940, Rayon Text. Mon., 21, 563.

18. The Thermal Conductivity of Textile Materials and Fabrics, J.B. Speakman and N.H. Chamberlain, 1930, J. Text. Inst., 21, T29.

19. A Practical System of Units for the Description of the Heat Exchange of Man with his Environment, A.P. Gagge, A.C. Burton and H.C. Bazett, 1941, Science, 94, 428.

20. The Transmission of Heat Through Textile Fabrics, E.E. Clulow and W.H. Rees, 1968, J. Text. Inst., 59, 285.

21. W.E. Morton and J.W.S. Hearle, Physical Properties of Textile Fibres, The Textile Institute (1962).

22. The Transfer of Heat and Moisture Through Clothing Fabrics, D.R. Gillings, D.S. Cooper and T.L. Dickins, 1972, Army Personnel Research Establishment, Report No. 44/72.

23. Thermal Insulation of Single and Multiple Layers of Fabrics, M.A. Morris, 1955, Text. Res. J., 25, 766.

24. The Transmission of Heat Through Textile Fabrics, W.H. Rees, 1941, J. Text. Inst., 32, T149.

25. The Thermal Conductivity of a Multilayer Sample of Underwear Material Under a Variety of Experimental Conditions, G.F. Fonseca and H.J. Hoge, 1962, Quartermaster Research and Development Center, Pioneering Research Division, Technical Report PR-8.

26. Insulating Values of Fabrics, Foams and Laminates, C.J. Monego et al, 1963, Amer. Dyest. Rep., 52, 21.

27. The Transmission of Heat Through Textile Fabrics, F.T. Peirce and W.H. Rees, 1946, J. Text. Inst., 37, T181.

28. Moisture Transfer Through Impermeable Foams, G.F. Fonseca, 1967, Text. Res. J., 37, 1072.

29. The Thermal Conductivity of Textiles, S. Baxter, 1946, Proc. Phys. Soc. (London) 58, 105.

30. Thermal Insulation of Air Force Clothing, J.F. Hall and J.W. Polte, 1960, Biomedical Lab. Aerospace Medical Division, Wright Air Development Division, WADD Tech. Rep. 60-597.

31. The Thermal Conductivity of Selected Flannel and Serge Fabrics Before and After Wear, E.L. Phelps, M.A. Morris and L.O. Lund, 1956, Amer. Dyest. Rep. 45, 181.

32. Effect of Laundering and Starching on Insulation and Vapor Permeability of Standard Fatigues, C.A. Levell, J.R. Breckenbridge and R.F. Goldman, 1970, Text. Res. J., 40, 281.

33. Mechanism of Heat Flow in Fibrous Materials, J.L. Finck, 1930, Research N.B.S. 5, 973.

34. A Study of Comfort Properties of Cold Weather Clothing, N. Hollies, 1956, Headquarters Research and Development Command, Textile Clothing and Footwear Division, Textile Engineering Laboratory Report, No. 164.

35. The Measurement of the Thermal Insulation of Textiles in Wind, C.D. Niven, 1956, Can. J. Technol. 34, 254.

36. Thermal Properties of Fur, H.T. Hammel, 1955, Am. J. Physiol. 182, 369.

37. Heat Conductivity of Fabrics, J.W. Hunt, 1951, Defence Research Board, unpublished work.

38. The Effect of Humidity on the Thermal Conductivity of Wool and Cotton, H. Staff, 1925, Proc. Am. Phys. Soc., 25, 252.

39. Some Thermal Properties of Fabrics, N.R.S. Hollies and H. Bogaty, 1965, Text. Res. J., 35, 187.

40. Diffusion in Solids, Liquids, Gases, W. Jost, Academic Press Inc., Publishers (1952).

41. The Mathematics of Diffusion, J. Crank, Oxford at the Clarendon Press (1956).

42. Diffusion in Absorbing Media, P.S.H. Henry, 1939, Proc. Roy. Soc., London, 171, 215.

43. American Standards on Testing and Materials, E 96-66 (reapproved 1972) 1973 Annual Book of ASTM Standards, Part 14.

44. American Standards on Testing and Materials, C 355-64 (reapproved 1973) 1973 Annual Book of ASTM Standards, Part 14.

45. The Relationship of Moisture Vapour Transmission to the Structure of Textile Fabrics, L.I. Weiner, 1970, Text. Chem. Color., 22, 378.

46. The Measurement of the Resistance of Materials to Water Vapour Diffusion by the Control Dish Method, J.E. Kennedy and L.H. Turl, 1961, DRML Project No. 121, Defence Research Board.

47. Diffusion of Water Vapour Through Textiles, L. Fourt and M. Harris, 1947, Text. Res. J., 17, 256.

48. Canadian Government Specifications Board, Canadian Standard Textile Test Methods 4-GP-2, No. 49.

49. The Resistance of Fabrics to the Passage of Water Vapour by Diffusion, M.E. Whelan, L.E. MacHattie, A.C. Goodings and L.H. Turl, 1955, Text. Res. J., 25, 211.

50. Moisture Transfer in Textile Systems, A.H. Woodcock, 1962, Text. Res. J., 32, 628.

51. Diffusion of Water Vapour Through Textile Materials, P. Nordon and J.G. Downes, 1965, J. Text. Inst., 56, T438.

52. Foam-Backed Textiles: A New Laminating Machine and the Properties of a Range of Laminates, R.V.R. Subramanian, 1967, J. Text. Inst. 58, 593.

53. Moisture Characteristics of Some Knit Fabrics Made from Blended Yarns, B.A. Knight, S.P. Hersh and P. Brown, 1970, Text. Res. J., 40, 843.

54. Measurement of Water Vapour Permeability of Textile Fabrics, F.T. Peirce, W.H. Rees and L.W. Ogden, 1945, J. Text. Inst., 36, T169.

55. WVT Through Multiple Barriers, K.W. Ninnemann and L.E. Simerl, 1961, Mod. Pack. 137.

56. Heat Transfer in Porous Media Containing a Volatile Liquid, A.H. Nissan, D. Hansen and J.L. Walker, 1963, Chem. Eng. Progr. Symp. Ser. 59, 114.

57. Heat Transfer Characteristics of Porous Rocks, D. Kunii and J.M. Smith, 1960, Am. Inst. Chem. Eng. J., 6, 71.

58. Calculation of the Thermal Conductivity of Porous Media, W. Woodside, 1958, Can. J. Phys., 36, 815.

59. Thermal Conductivity of Compressible Porous Materials, D.G. McMaster, 1964, Tappi, 47, 796.

60. Heat Transfer in Porous Bodies at Various Temperatures and Moisture Contents, L. Herminge, 1961, Tappi, 44, 570.

61. Thermal Conductivity of Insulation Containing Moisture, F.A. Joy, 1957, Symp. Am. Stand. Test Meth. 65.

62. Thermal Conductivity of Moist Materials and its Measurements, H.B. Jespersen, 1953, J. Inst. Heat. Vent. Eng., 21, 157.